Marasco, P. L. (2002). The impact of helmet-mounted display visor spectral characteristics on visual performance. *Proceedings of SPIE – The International Society for Optical Engineering Helmet- and Head-Mounted Displays VII, USA, 4711*, 174-184.

The Impact of Helmet-Mounted Display Visor Spectral Characteristics on Visual Performance

Peter L Marasco*
Air Force Research Laboratory
Human Effectiveness Directorate

ABSTRACT

Visors are an important element in modern helmet-mounted displays (HMDs). In addition to their more conventional use as eye protection, they can be used as the final element in the optical system that relays visual information to the observer. To enhance their usefulness as the final optical element (as a beam splitter or image combiner), visors are sometimes coated to increase their reflectivity, improving the efficiency of the optics. However, pilots often object to the addition of reflective patches on their visors, indicating, among other reasons, that they decrease observed target contrast and, therefore, decrease target detection range. This paper will examine the impact of the additional reflective coating on visual performance through a helmet-mounted display visor. It will propose some design parameters on the spectral nature of the coating that might make it more useful to both the HMD designer and to the HMD wearer. Finally, this paper will examine visual phenomena that may affect visual performance through a coated visor.

Key Words: Helmet-mounted display, HMD, Visor, Visual performance, Coatings

1. INTRODUCTION

The visor is a critical part of the pilot's equipment. In most cases, it is one of at least two transparencies (visor and windscreen) through which they must look to see the world around him. Both transparencies can have a significant impact on the pilot's visual performance. The optical properties of both the visor and the windscreen, including transmission, reflection, distortion, and their tendency to scatter light, play an important role in the quality of image a pilot can see through them.

Visors have evolved into an important part of modern helmet-mounted displays (HMDs). To simplify the optical design, in terms of the number of optical elements needed, the helmet visor can be used as the beamsplitter, reflecting the HMD imagery into the pilot's eyes while still allowing him to see the targets of interest. This final reflection can rely on the Fresnel reflectivity inherent to the visor or can be enhanced by use of coatings. Coatings of interest can enhance the reflection of the visor as much as desired. Unfortunately, these reflection-enhancing coatings are known to have a negative impact on the pilot's visual performance. Many pilots have noticed a significant and unacceptable reduction in the distance at which they can engage a target, or "Tally Ho" distance [Kocian and Task 2000]. However, HMDs that employ uncoated visors must rely on very luminous image sources to ensure that enough light reaches the pilot's eyes. This tends to shorten image source lifetime and preclude the use of certain image sources in these HMD designs.

To examine the impact of visor coatings, one must start with the assumption that reductions in visual performance are due exclusively to a loss of target contrast. As shown in Figure 1, this paper will define L_T as the luminance of the target, L_B as the luminance of the target background, E_s as the external illumination falling on the visor, and L_H as the luminance of the HMD display that reaches the observer's eyes. Using this notation, the true contrast (Michaelson or modulation contrast) of the target, of luminance L_T, with its background, of luminance L_B, can be expressed as:

* Peter.Marasco@wpafb.af.mil; phone 1 937 255-0881; fax 1 937 255-8366; http://www.hec.afrl.af.mil/; Human Effectiveness Directorate, Air Force Research Laboratory, AFRL/HECV, 2255 H Street, Bldg. 248, Rm. 300, Wright-Patterson AFB, OH, USA 45433-7022

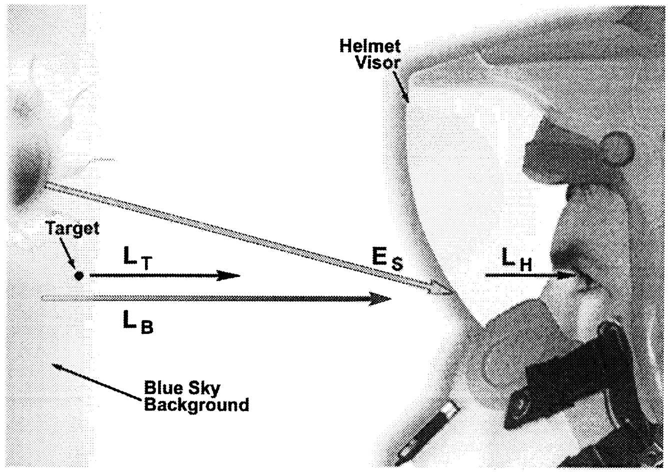

Figure 1. Graphical description of parameters affecting observed contrast.

$$C_T = \frac{|L_T - L_B|}{L_T + L_B} \tag{1}$$

The primary reason for this loss of observed contrast is the veiling luminance stemming from scattered light from the visor and from facial reflections. To incorporate the impact of scatter and reflections on the perception of target contrast, a veiling luminance, L_V, can simply be added to the target and background luminances in Equation 1. This approach was used in other papers [Marasco and Task 2001] [Kocian and Task 2000] and treats the veiling luminance as if it originates at the visor, not propagating through it like the light from the target. Therefore, the impact of visor transmission, T_V, on perceived contrast must be included. This is achieved by multiplying L_T and L_B by T_V. These modifications of Equation 1 change the equation from one describing the true contrast of the target to an equation for the contrast seen from the observation point, or observed contrast, C_o.

$$C_o = \frac{|(T_V L_T + L_V) - (T_V L_B + L_V)|}{(T_V L_T + L_V) + (T_V L_B + L_V)} \tag{2}$$

Assuming that L_B is greater than L_T, the above expression simplifies to:

$$C_o = \frac{C_T}{\frac{L_V(C_T + 1)}{L_B T_V} + 1} \tag{3}$$

To maximize C_o, one has few options as shown in Equation 3. L_B can be large but not on command. The engineer cannot control the sky or ground luminance. L_V can be made small, but only so small. Recall that:

$$L_V = L_{Vs} + L_{Vf} \tag{4}$$

Here, L_{Vs} and L_{Vf} are the veiling luminance caused by scatter from the transparency and the veiling luminance from facial reflections, respectively. The veiling luminance caused by visor scatter is a function of a number of parameters including the incident illuminance (E_s) and the sample's inherent tendency to scatter light, symbolized by a function S_v. The sample's ability to scatter has been shown to be a function of the illumination and observation geometry and the wavelength of the illumination, λ [Marasco 2000]. Stated simply, $L_{Vs} = E_s S_V$. If one assumes a Lambertian reflection and keeping in mind that $E_s = M = \pi L$ [Boyd 1985] where M is the luminous exitance and L is luminance, the luminance of the pilot's face, L_f, can be described as:

$$L_f = \frac{1}{\pi} E_s T_V R_f \tag{5}$$

Here, R_f is the reflectivity of the pilot's face. When this light is reflected back to the pilot by the visor, it contributes to L_V. The veiling luminance due to facial reflections as seen in the visor, L_{Vf}, can therefore be expressed:

$$L_{Vf} = \frac{1}{\pi} E_s T_V R_f R_V \tag{6}$$

Here, R_V is the reflection from the inside surface of the visor. Eliminating scatter from the visor and reflections from the pilot's face is difficult if not impossible. And even if scatter can be eliminated from new visors, it will increase as the visors age and become scratched from wear and handling.

The only parameter in Equation 3 that the engineer can use to improve observed contrast is the visor transmission. T_V can be made as large as possible, thus improving the target's observed contrast (Figure 2). In Figure 2, observed contrast is plotted as a function of transmission for a number of conditions described by the ratio of the veiling luminance to the background luminance (L_V/L_B). This parameter is used to indicate how much stronger than veiling luminance the background luminance is. When L_V/L_B is small, the background luminance dominates the ratio, improving visual performance by overwhelming the veiling luminance. When LV/LB is large, scattered light dominates, reducing visual performance. One should also note from Figure 2 that visor transmission can significantly influence observed contrast, especially when transmission is below 20%.

Dielectric stack coatings can be designed to build reflectors that are spectrally selective. Such coatings can be designed to reflect strongly at some wavelengths while functioning as an antireflection coating at others, reflecting nearly nothing. This property of dielectric stack coatings can be exploited to build a visor reflector for HMD applications that maximizes visor transmission, thus increasing the visibility of targets seen through the visor, while increasing the amount of light presented to the pilot by the HMD optics.

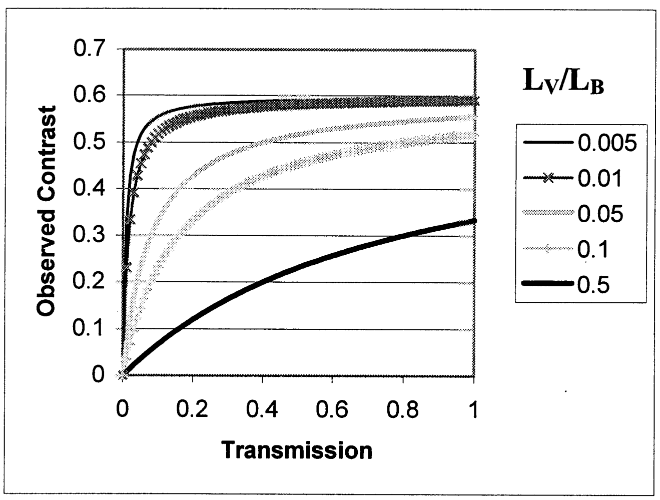

Figure 2. The effect of transmission on observed contrast for a 60% contrast target.

2. EFFECT OF SPECTRAL TRANSMISSION AND REFLECTION

Up to this point, this paper has treated many parameters as constants with respect to wavelength. However, many, if not all, parameters discussed are functions of wavelength. For example, the Fresnel surface reflections are often treated as relatively constant with respect to the visible spectrum but actually exhibit distinct wavelength dependence. Figure 3 is a plot of the index of refraction of two popular plastics as a function of the wavelength of light. Using established relationships, the Fresnel reflection for polycarbonate can be calculated (Figure 4). This is a plot of the reflectivity of a bare polycarbonate surface inclined at a number of incidence angles. One can see from Figure 4 that even an uncoated piece of plastic reflects more strongly in blue light than in red. The Fresnel reflectivity of many optical materials, including glass, is a function of wavelength and incidence angle. One should note that the reflectivities plotted in Figure 4 are the average of s and p polarized light. The reflectivity of each can be noticeably different (Figure 5). At a 45-degree angle of incidence, similar to what is used in some helmet-mounted display designs, the bare polycarbonate visor reflects predominantly s-polarized light. However, for unpolarized sources, the reflectivity of the surface is the average of the s- and p-polarized components. The resulting surface reflectivity is considerably less for unpolarized sources.

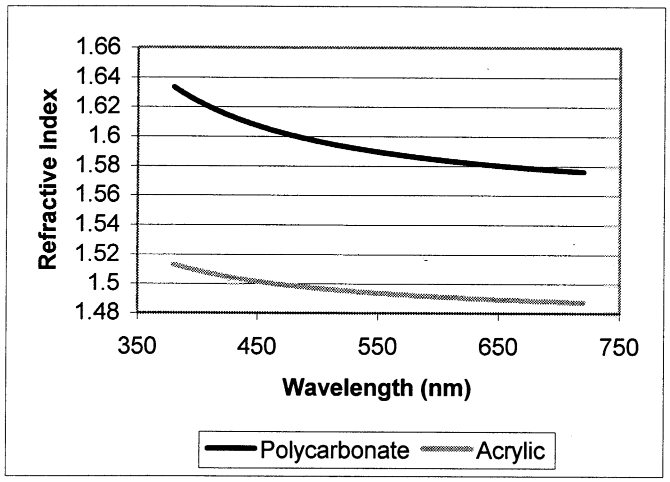

Figure 3. Index of refraction of two plastics plotted as a function of wavelength.

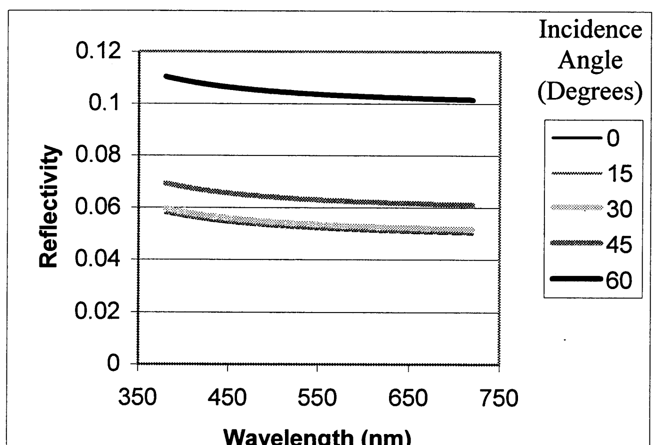

Figure 4. The reflectivity of polycarbonate plotted as a function of wavelength for five angles of incidence, in degrees.

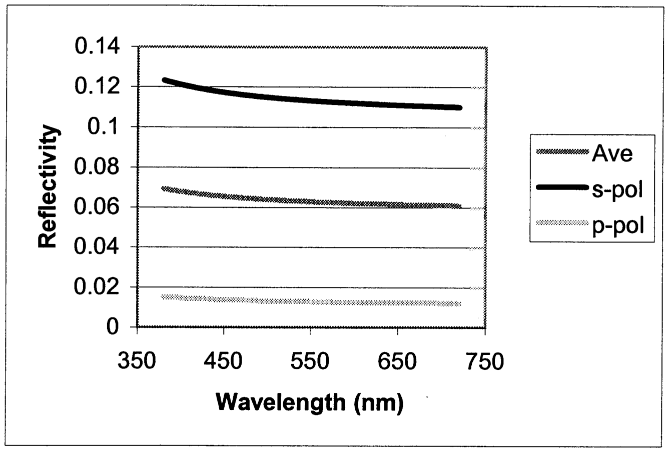

Figure 5. The average reflectivity of polycarbonate as a function of wavelength and its reflectivity for s- and p-polarized light.

Thin dielectric stacks have been used to create coatings with spectrally complex reflectivities and transmissivities. If dielectric stack reflectors are employed on the visor, this spectral complexity can be exploited to achieve several interesting results. A good coating should do more than just reflect the image source of the HMD. One could, theoretically, be tuned to give the desired reflection of the HMD while transmitting a large percentage of visible light from the target. This can be accomplished by redistributing the reflectivity inherent in the visor surface. Fresnel reflection for a polycarbonate visor is about 6% per surface (12% per visor). If the visor could be antireflection coated in parts of the visible spectrum not needed to reflect the HMD image source, this loss could be recovered for wavelengths other than those reflected for the display. One could think of the approach as "stacking up" the surface reflectivity where desired. This approach works particularly well with narrow emission band phosphors. Coatings can be optimized to reflect the primary emission while antireflection coating the surface for all other visible wavelengths.

2.1 Basic Photometry and Coating Design

It is easy to see how the amount of visible light available influences an observer's vision. This paper employs photometric quantities to describe light. To calculate the amount of visible light available, L_{Vis}, from a source of spectral radiance $L(\lambda)$, one must apply the following equation [Boyd 1985]:

$$L_{Vis} = k \int_0^\infty V(\lambda) L(\lambda) d\lambda \qquad (7)$$

This equation describes the summation of all light from the source over all wavelengths, weighted by the spectral response of the human eye, $V(\lambda)$ (Figure 6). To complete the calculation, the integral is multiplied by k, the luminous efficacy, a constant used to convert radiometric units to photometric units. For example, this integral can be interpreted graphically to calculate the amount of visible light emitted from the P43 phosphor (Figure 7). To do this, one would multiply Figure 6 by Figure 7, sum the individual components over all visible wavelengths and then multiply by k, yielding the amount of visible light (luminance) emitted from the P43 phosphor in photometric units. The above equation can be modified and used to calculate the impact of filters and reflectors on the amount of visible light available by including the spectral nature of the reflector inside the integral. For a reflector, $R(\lambda)$, the equation becomes:

$$L_{Vis} = k \int_0^\infty V(\lambda) R(\lambda) L(\lambda) d\lambda \qquad (8)$$

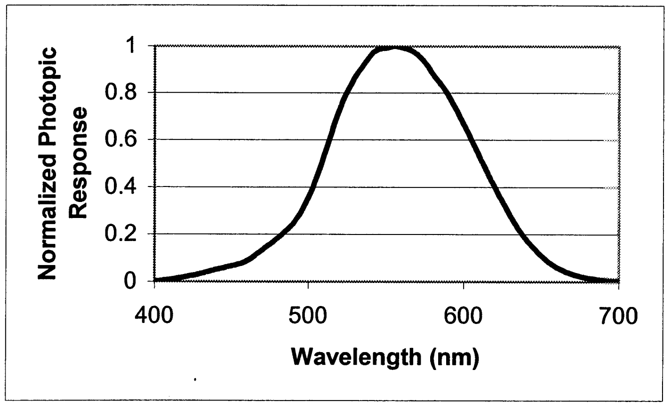

Figure 6. Photopic response of the human eye [Wyszecki and Stiles 1982].

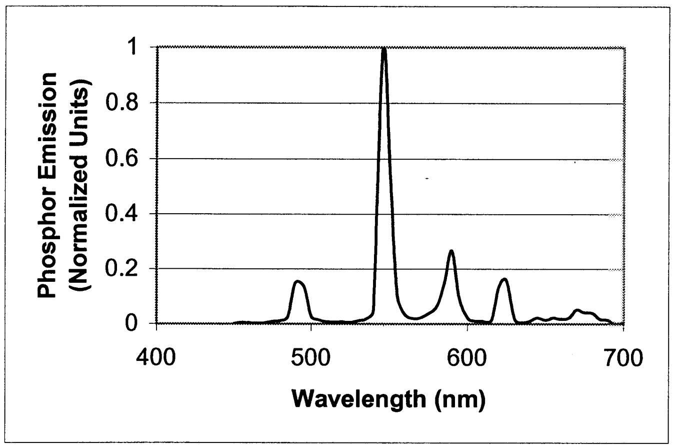

Figure 7. Normalized P43 phosphor emission.

This integral can also be expressed graphically as the multiplication of Figure 6 by Figure 4 and Figure 7, the summation of the individual components over visible wavelengths, and then multiplication by k. The result is the amount of visible light emitted from the P43 phosphor that is reflected from a polycarbonate visor inclined at 45 degrees. Using this approach, the amount of light reflected can be expressed as a percentage by dividing the reflected light by the incident light. In terms of the integrals used earlier, this ratio can be described as:

$$R_{source} = \frac{k \int_0^\infty V(\lambda)R(\lambda)L(\lambda)d\lambda}{k \int_0^\infty V(\lambda)L(\lambda)d\lambda} \times 100\% \qquad (9)$$

If this is applied to the P43 example, one will find that 6.3% of the visible light from a P43 phosphor will be reflected from an uncoated polycarbonate visor, inclined at 45 degrees. Using a similar development and by applying the fact that T = 1 – R, the photopic transmission of a surface can be expressed:

$$L_{Vis} = k \int_0^\infty V(\lambda)T(\lambda)L(\lambda)d\lambda = k \int_0^\infty V(\lambda)(1 - R(\lambda))L(\lambda)d\lambda \qquad (10)$$

or as a percentage of the total incident light using:

$$T_{Photopic} = \frac{k\int_0^\infty V(\lambda)T(\lambda)L(\lambda)d\lambda}{k\int_0^\infty V(\lambda)L(\lambda)d\lambda}\times 100\% = \frac{k\int_0^\infty V(\lambda)(1-R(\lambda))L(\lambda)d\lambda}{k\int_0^\infty V(\lambda)L(\lambda)d\lambda}\times 100\% \qquad (11)$$

2.2 Coating Design

This treatment will restrict analysis to the transmission and reflection of the inner surface of the visor. One should keep in mind that the overall transmission of the visor is a function of two surfaces and the bulk material. However, since the coating on the visor's inner surface cannot influence the transmission or reflection of the other two contributors, they will be ignored when comparing coatings.

The goal of this effort is to design a coating such that the reflectance of the source is as high as it needs to be while maximizing photopic transmission through the visor. To improve the pilot's visual performance, the visor's photopic transmission must be approximately equal to the photopic transmission of an uncoated visor surface. One must therefore calculate visible light transmitted through the final visor surface. The photopic transmission of the target's background, as seen through a visor, can be expressed using Equation 10 by replacing $T(\lambda)$ with the spectral properties of the visor's rear surface, denoted as $T_V(\lambda)$ if the surface is uncoated, and inserting the spectral properties of the target's background ($L(\lambda)$). If the visor is coated, replace $T(\lambda)$ with the spectral properties of the visor's rear surface coating, denoted $T_{VC}(\lambda)$, and perform the appropriate integration.

This approach is consistent with the assumption made earlier that the target background is brighter than the target itself. If this is not the case, one should calculate the photopic transmission of the target seen through a visor. This can be expressed using Equation 10 and inserting the spectral properties of the target itself ($L(\lambda)$) and the appropriate visor transmission.

The second parameter to examine is the reflection of the HMD image source from the visor. This is important to ensure the observer receives sufficient light from the HMD to make the symbology visible. The photopic reflectance of the image source by the visor can be calculated using Equation 8 by replacing $R(\lambda)$ with the spectral properties of the visor's rear surface, denoted either $R_{VC}(\lambda)$ or $R_V(\lambda)$, depending on whether the visor is coated or not, and inserting the spectral emission of the HMD source ($L(\lambda)$).

2.3 Optimization

The number of degrees of freedom afforded the engineer by the design can limit optimization of a coating. The simplest coating that might yield the performance required is an antireflection coating with a partially reflecting notch (Figure 8). Designing and optimizing a coating of this nature affords the engineer three primary parameters to manipulate: the reflectivity of the coating within the HMD image source emission band, the width of the reflection band for the HMD source, and the quality of the antireflection coating outside the notch. One could argue that the location of the reflective notch is a fourth parameter. Unfortunately, the selection of the HMD image source will place this parameter beyond the control of the engineer. To minimize the impact of the coating on pilot visual performance, it is recommended that the coating be optimized to transmit visible light equal to the transmission of the uncoated visor surface. The three primary parameters can be combined to yield coatings that transmit as much light as the uncoated visor surface, minimizing the impact of the visor coating, while reflecting significantly more light from the HMD. Some of these parameters will have a stronger impact on the coating performance than others. For example, the width and reflectivity of the notch will strongly influence the amount of HMD image source light available to the pilot. Reducing the reflectivity of the antireflection coating outside the reflective notch may have little impact on the total transmitted light.

3. EXAMPLE COATING DESIGN

3.1 Performance Benchmarks

Two visors historically used on head and helmet mounted displays set performance benchmarks for the technology: the standard polycarbonate visor without a reflective coating and the polycarbonate visor with a 13% reflective metal partial mirror. The standard neutral gray visor without a reflective coating is considered acceptable for target detection ("Tally Ho") but does not reflect much HMD light, requiring a bright HMD image source. Visors with a metallic coating reflect plenty of HMD light but are not acceptable for target detection. Metallic coatings are considered to have a detrimental impact on "Tally Ho" distance due to the associated transmission loss. A solution lies somewhere in between.

The first surface examined here is the uncoated polycarbonate. Two figures of merit of interest are the surface's transmission of all visible light, T_{Phot}, and its reflection of the visible light from the P43 phosphor, R_{P43}. To calculate T_{Phot}, one needs to know something about the nature of the light coming from the target background. Since there are virtually an infinite number of possible target backgrounds to consider, this paper will limit its analysis to one. The target background will be assumed to be spectrally uniform, or white, with all wavelengths considered to have equal radiance. This assumption will simplify the resulting calculation. Using the information displayed in Figure 4, Figure 6, and Equation 11, the photopic transmission of an uncoated polycarbonate surface was calculated to be 93.7%. The calculation of the percent of light from the P43 phosphor can be calculated using a similar approach. Using the information in Figure 4, Figure 7, Figure 6, and Equation 9, the photopic reflectivity of an uncoated polycarbonate surface was calculated to be 6.3%. This result should have been expected because of the nature of the visor reflectivity. It reflects all wavelengths of approximately equal radiance.

The results from the analysis of the metallic reflective surface were equally predictable. Since metallic coatings exhibit relatively uniform reflectivity in the visible region of the spectrum, the 13% reflective surface was modeled as a perfectly uniform, 13% reflector at all visible wavelengths. Using this model, the information in Figure 6, and Equation 11, the photopic transmission of the metal surface was calculated to be 87%. In addition, the reflectance of the light emitted from the P43 phosphor was calculated using a similar approach and Equation 9 to be 13%. One should note that the metal reflects twice as much photopic energy from P43 as the uncoated visor. In addition, one should note that the difference between the photopic transmissions of the two surfaces is only 6.7%. It is surprising that such a small difference in visor transmission can have a significant impact on visual performance. This emphasizes the need to design a visor reflective coating that maximizes photopic transmission.

3.2 Example Design

From the previous analysis, one can conclude that some HMD systems require a reflectivity about twice that of the uncoated visor to provide adequate light from the HMD image source to the observer. It is also easy to see the need for high photopic transmission. Fortunately for the coating design, HMDs tend have image sources that use phosphors with fairly strong, spectrally narrow primary emissions. This tendency can be exploited to design a visor reflector that begins to look like an antireflection coating with a slight reflective spike (Figure 8).

This example design assumes the HMD image source will use a P43 phosphor. As a result, the spectral width and location of the visor coating reflection were chosen to correspond with the primary green emission of the P43 phosphor (Figure 7). The example coating's notch falls between 530 and 565 nm. The next step was to choose the quality of the antireflection coating outside of the reflection notch. To improve the photopic transmission, an average reflection of 0.5% was chosen. This parameter may be limited by manufacturing issues not addressed in this paper. However, once the quality of the antireflection coating and the width of the reflective notch are chosen, only the average reflection inside the reflective notch remains undetermined. Using the parameters established for the coating and Equation 11, the average notch reflectivity was calculated such that the coating's photopic transmission was equal to the transmission of the uncoated polycarbonate surface. The resulting reflectivity was calculated to be 17.1%. Using the approach outlined earlier and Equations 9 and 11, the example coating's photopic transmission and P43 reflection were then calculated. This coating yielded a photopic transmission of 93.7% and a P43 reflectivity of 12%.

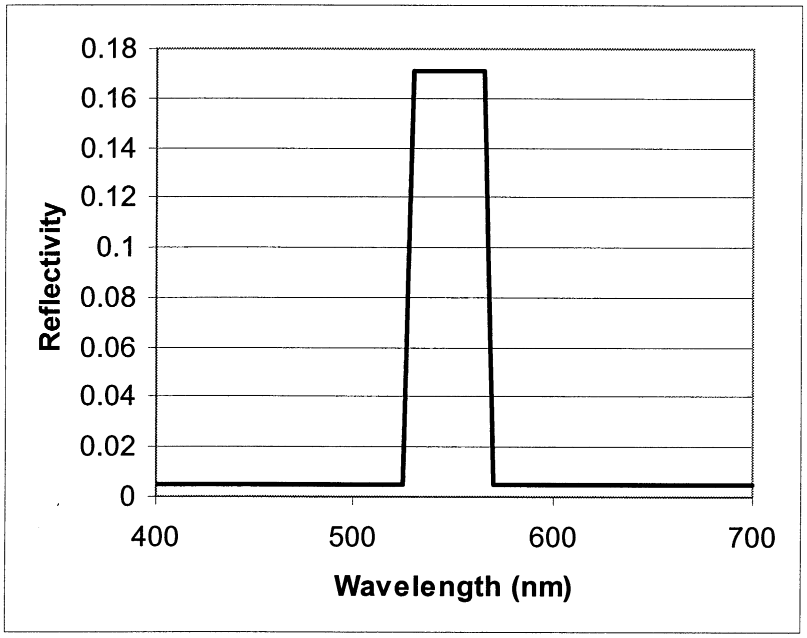

Figure 8. Spectral reflectivity for a potential visor coating.

Table 1. Transmissivity of visible light and reflectivity of P43 phosphor emission for three visor coatings

Coating	T_{Phot}	R_{P43}
Uncoated Polycarbonate	93.7 %	6.3 %
Metallic Reflector (13 %)	87.0 %	13.0 %
Example Design	93.7 %	12.0 %

4. DISCUSSION

4.1 The Impact of Luminance Transmission

In adding a reflecting coating to a visor, the additional luminance transmission loss should be insignificant for spectrally narrow reflectors of peak reflectivity of 50% or less. One should keep in mind that the current visor can transmit as little as 10% of the available light. The addition of such a coating could drop the transmission of a particular narrow spectral band to, at most, 5% while leaving the visor's transmission over the rest of the visible spectrum unchanged. However, if this proves to be a problem, one conceivable solution would be to alter the absorption of the visor to make it more transmissive in the same place, spectrally, as the coating is more reflective (Figure 9). The combination of the two would then yield an overall transmission similar to the standard, uncoated visor.

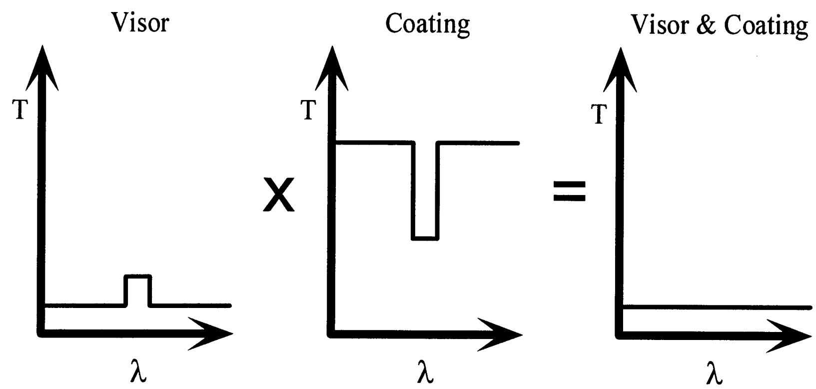

Figure 9. Graphical representation of the combination of visor and coating transmission.

4.2 The Impact of Color Perception

The potential exists for spectrally non-neutral coatings to influence an observer's perception of color. Such color shifts should be investigated for each coating and visor combination using conventional techniques for calculating the color coordinates of cockpit displays, as seen through both uncoated and coated visors, and determining the magnitude of the coordinate shift induced by the coating, such as those outlined by Wyszecki and Stiles [Wyszecki and Stiles 1982]. One then must consult the body of literature on color naming and color recognition to determine if the induced color shift will inhibit an observer's ability to correctly identify the colors presented by the display. The tolerances on color coordinate shift are expected to be fairly large [Post and Calhoun 1988]. However, should color perception become problematic, the approach described in the previous section of altering the absorption of the visor, making it more transmissive where the coating is more reflective (Figure 9), could be applied. Therefore, the impact on color perception is expected to be minimal.

5. CONCLUSIONS

Visor coatings can be engineered to increase the amount of photopic energy available to the observer while minimizing unwanted visual phenomena and minimizing the impact on "Tally Ho" distance. To increase visor transmission, a modified antireflection coating can be applied to the rear surface. This coating effectively "stacks up" reflectivity in a spectral region where the HMD source is strong, such as in the green for the P43 phosphor, while minimizing it everywhere else in the visible spectrum. The end result is a visor surface that transmits more light than an uncoated surface but reflects more HMD light also. Increasing visor photopic transmission increases perceived target contrast and, therefore, increases "Tally Ho" distance. This strategy also enables one to gain the added benefit of minimizing unwanted reflections from the pilot's own face and eyes.

The impact of the visor coating should be minimal. Its effect on overall luminance transmission should be small because of the absorbing dye that tints the daytime visor. The amount of energy from the outside world affected by the coating is small when compared to the visor tint. This tint can absorb more than 50 to 80% of the incident light, depending on how dark the visor is. Color shifts are expected to also be insignificant. The spectral reflections exploited could be 10 to 50% depending on the luminance and spectral characteristics of the HMD source. In addition, the human tolerance for color naming is fairly large and should be adequate to overcome color coordinate shifts induced by the visor coating. Finally, should either luminance transmission or color perception be significantly impacted, compensation can be made for both in the absorption of the visor tint.

ACKNOWLEDGEMENTS

The author would like to acknowledge the help of Paul Havig and Alan Pinkus, both of AFRL/HECV, Human Effectiveness Directorate, Air Force Research Laboratory, for their assistance in deciphering certain aspects of visual perception.

REFERENCES

Boyd, R.W., *Radiometry and the Detection of Optical Radiation*, John Wiley & Sons, New York, 1983.

Dereniak, E.L., Crowe, D.G., *Optical Radiation Detectors*, John Wiley & Sons, New York, 1984.

Kocian, D.F, Task, H.L., "Measurement of military helmet and head-mounted display (HMD) visor optical properties," *Head- and Helmet-Mounted Displays V*, 4021-13, AeroSense Symposium, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, pp 120-132, 2000.

Marasco, P.L., "An examination of optical scatter from aerospace transparencies and its effect on vision," Ph.D. Dissertation, University of Dayton, 2000.

Marasco, P.L., Task, H.L., "Measurement of visual performance through scattering visors and aerospace transparencies," *Head- and Helmet-Mounted Displays VI*, 4361-20, AeroSence Symposium, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, pp 188-197, 2001.

Post D.L., Calhoun, C.S., "Color-name boundaries for equally bright stimuli on a CRT: Phase II," *1988 Society for Information Display International Symposium Digest of Technical Papers*, **19**, pp 65-68, 1988.

Wyszecki, G., Stiles, W.S., *Color Science: Concepts and Methods, Quantitative Data, and Formulae*, John Wiley & Sons, New York, 1982.